Model Performance Evaluation of CACTUS

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Sandia National Laboratories
November 15, 2013

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CACTUS is a hydrokinetic turbine performance code under development at Sandia National Laboratories (SNL). Details on it capabilities are given in [1]. CACTUS simulates arbitrary geometries, including cross-flow and axial flow rotors. SNL added new capabilities to CACTUS and an outreach effort was begun to solicit interest among MHK researchers and developers who want to consider CACTUS for hydrokinetic turbine design and analysis. As part of this outreach campaign SNL developed a User's Manual and evaluated the performance of the CACTUS code using measured performance curves from three different MHK experiments detailed below.

Sandia Rotor

The Sandia turbine (Figure 1) is a 3 bladed constant pitch axial flow turbine with a diameter of 5 m designed for optimal hydrodynamic performance. It uses the MHKF1 family of three hydrofoils. A 1:8.7 scale model was tested at the Applied Research Laboratory (ARL). A CACTUS model was done, and the CACTUS geometry is shown in Figure 2. The geometry was created using the Matlab geometry creation scripts included within CACTUS. The foil data was obtained by using Xfoil (a popular code for 2D airfoil analysis) to obtain the coefficients for a range of angle of attack up to stall. The results were then extrapolated using the Viterno method from an NREL Airfoil Prep spreadsheet. This was done for each of the three airfoils and for 9 different Reynolds number.

The rotor performance results of the CACTUS simulation are compared to the experimental data from ARL in Figure 3. Very good agreement is observed for all tip speed ratios (TSR).

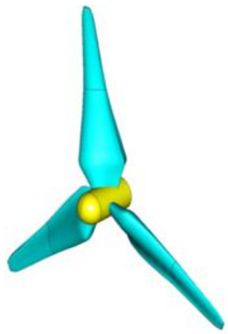

Figure 1-CAD drawing of Sandia turbine

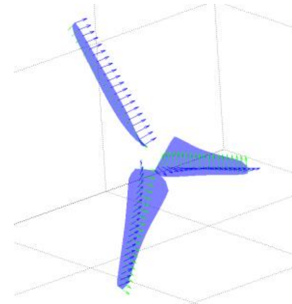

Figure 2- CACTUS geometry for Sandia turbine

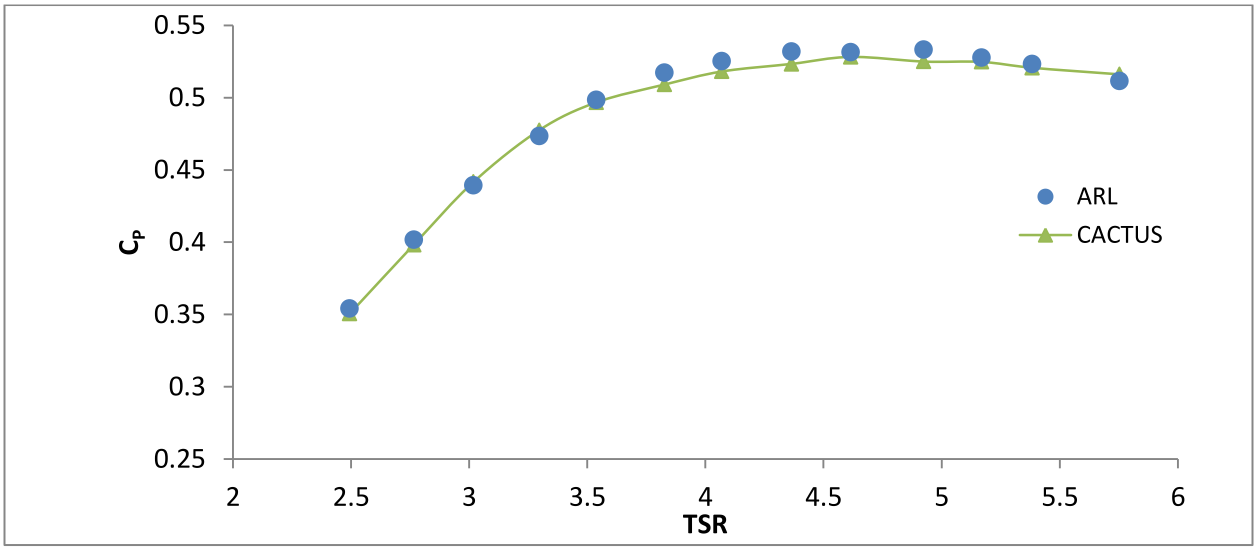

Figure 3- Comparison of power coefficient between experiment and CACTUS simulation.

UNH Experiment

A three bladed, vertical axis, cross flow turbine with straight, constant chord blades was tested at the University of New Hampshire. The turbine geometry and dimensions are shown in Figure 4. The design was meant to be a simple version of DOE's reference model 2. A CACTUS model of this experiment was created, and the CACTUS geometry can be seen in Figure 5. The CACTUS results are compared to the experimental results in Figure 6.

The CACTUS results and experimental results do not agree. The lack of agreement was found to be due to a limitation of CACTUS when dealing with turbines with high blade chord-to-radius ratio. An instability in the free wake evolution due to local regions of upstream flow was observed when plotting wake trajectories and is believed to be caused by the high chord-to-radius ratio. The results plotted in Figure 6 suffer from this instability, which likely is the main contributor to the lack of agreement between experimental data and simulation. Fortunately the turbine used in this experiment has higher chord-to-radius ratio (c/R=0.28) than any anticipated MHK device. The actual reference model 2 has a much lower chord-to-radius ratio (max c/R=0.124) and a CACTUS simulation shows no wake instability issues. Hence, better agreement is anticipated.

Attempts to overcome the chord-to-radius limitation were based on altering the wake evolution by using more time steps per revolution and/or manually increasing the wake vortex core radius. The results of one such case using three times more iterations per revolution and a factor of 2.5 on the wake vortex core radius is shown in Figure 6 (CACTUS Modified). These techniques resulted in improved wake behavior and suggest that the chord to radius limitation could be overcome (or at least the wake stability issues) with better wake evolution methods. One potential problem of this solution would be the increase in computational time due to higher wake resolution. This could be addressed by decoupling the near and far wake models, allowing more time steps without significantly increasing the number of far wake elements (free vortex elements). If this does not completely fix the issue, more direct modeling of the viscous effects in the wake should be considered. In the meantime, the wake for any simulation with high chord-to-radius (c/R >~0.25) must be checked for instabilities. Fortunately most MHK devices have significantly lower chord-to-radius.

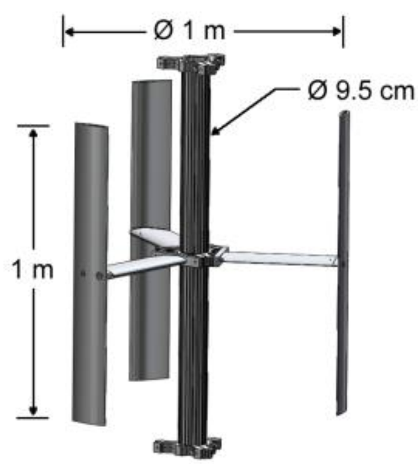

Figure 4- Dimensions of turbine tested at UNH

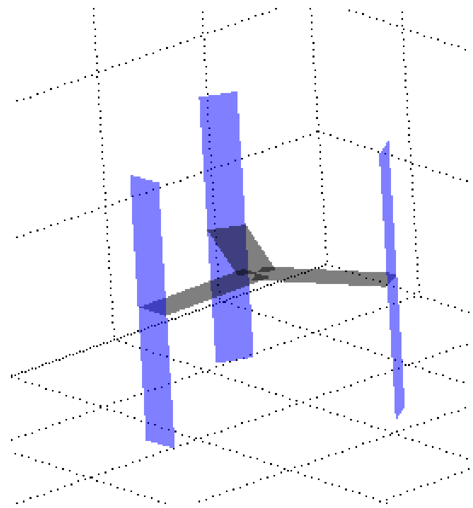

Figure 5- CACTUS geometry for UNH turbine

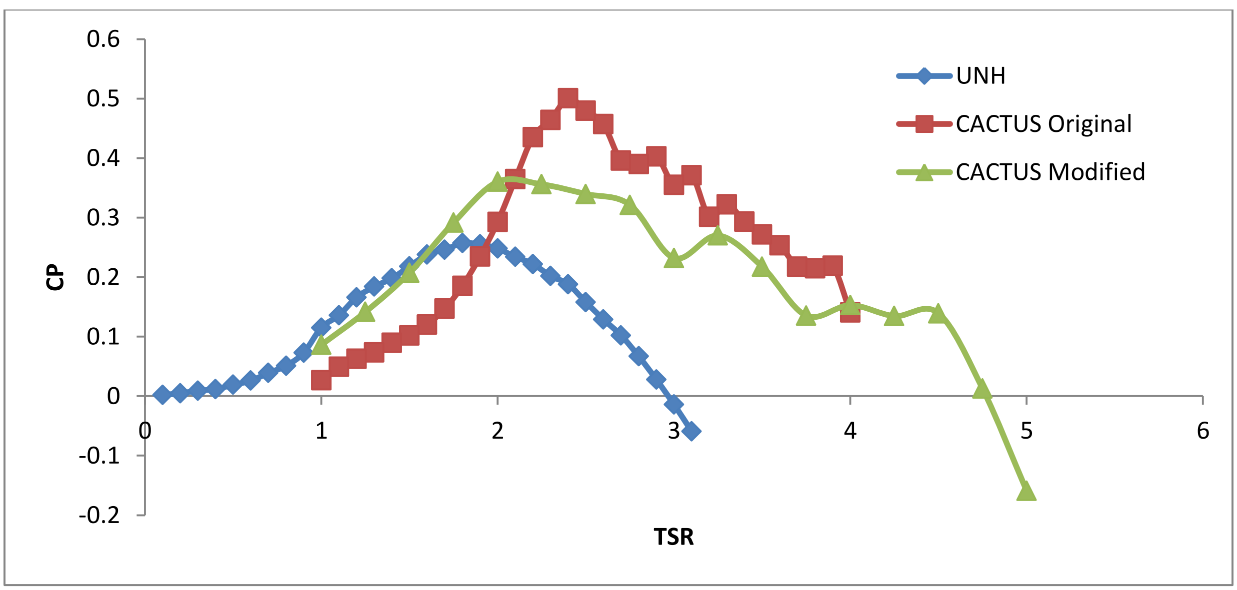

Figure 6- Comparison of power coefficient between experiment and CACTUS simulation.

USNA RM1

A 1:25 scale version of the DOE two-bladed axial flow reference model 1 turbine was tested at the United States Naval Academy. The scaled rotor has a diameter of 0.8m. A schematic of the test setup can be seen in Figure 7. A simplified CACTUS model was created, since the specific blade geometry could not easily be accurately represented. The blade transitions from NACA 63-618 foil sections to thicker foils, to elliptical sections of different aspect ratios, and finally to circular sections. Elliptical sections are generally very difficult to model and little empirical data for elliptical sections exists. Efforts obtaining 2D empirical data would be of little use since transition regions at the root of rotating blades are associated with 3D effects that wouldn't be captured.

The CACTUS results are compared to the experimental data in Figure 8. There are two sets of experimental data corresponding to two repetitions of the experiment. Two different CACTUS models were simulated. The first used only the NACA 63-618 foils throughout the entire span of the blade, completely ignoring the transition region. This model is denoted *'CACTUS-1Foil'* in Figure 8, and over predicts the power coefficient as expected. The second model, denoted *'CACTUS-1F+Cyl',* simulates half of the transition region as a circular cylinder, and under predicts the power coefficient.

Transition regions at the root of blades suffer from 3D effects not easily captured by CACTUS. Rotational augmentation is the occurrence of stall at higher angles of attacks and lift coefficients near the root of a rotating blade than for a two dimensional airfoil test. One way this has been addressed in the past is by using the NREL methods in the AirfoilPrep routine to create different airfoil tables for each blade section according to their radial location, which somewhat account for the rotational stall delay effect. This is undesirable because it is burdensome and might not be very accurate. Perhaps a better way to handle this, without having to apply individual corrections to each airfoil table used, would be to implement an integral boundary layer (IBL) calculation into CACTUS, which captures the 3D rotational effects. Some thought is needed to figure out how to best implement this in the context of a blade element method like CACTUS, which uses empirical airfoil tables rather than calculating the chord-wise velocity and load distribution on the blade section.

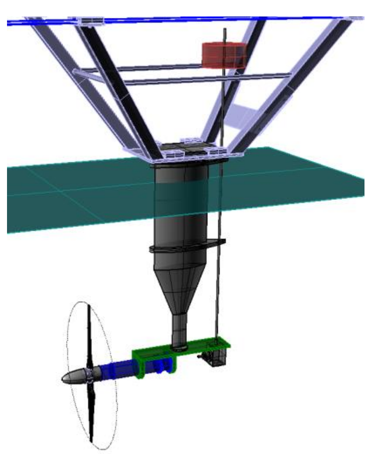

Figure 7- Test setup for the scaled RM1 tested at USNA

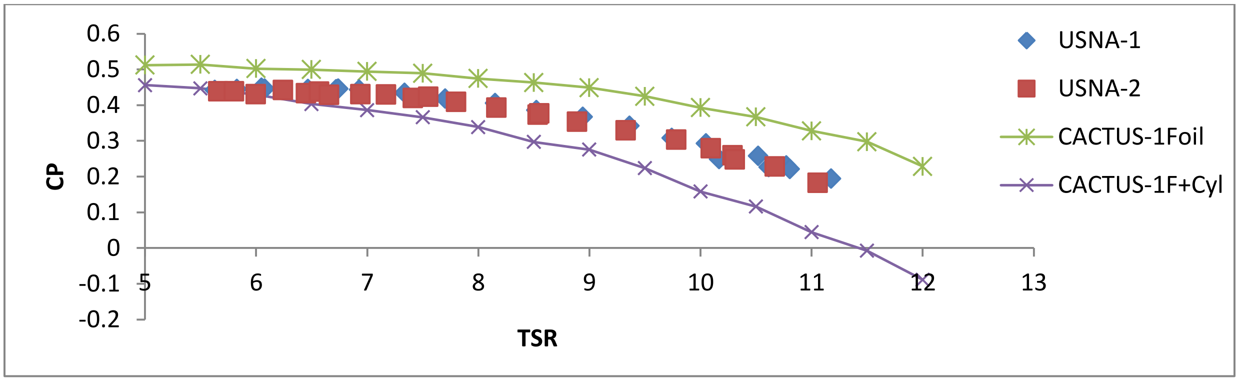

Figure 8-Comparison of power coefficient between experiment and CACTUS simulations.

Conclusions and Future Work

CACTUS model performance was evaluated with measurements collected in three different experiments. The results show that CACTUS can be very useful in many cases, but that it also has some limitations. Problems predicting performance for circular and elliptical blade geometries and high chord-to-radius rotors requires further investigation. Possible solutions to both issues were discussed in this report.

Our validation efforts will continue as more and more MHK experimental data becomes available, including performance measurements to be collected at St. Anthony Falls Laboratory in 2014 for a dual rotor axial flow turbine and a dual rotor cross flow turbine. Several other scaled model turbine test are underway or planned for the upcoming year. Once these are completed, CACTUS simulation will be done to serve as further validation.

Acknowledgements

The authors wish to thank David Maniaci for reviewing this report and for his input on model results discussions.

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